

TIME AND RATE MEASURES IN CHOICE TRANSITIONS

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Three experiments with pigeons studied the relation between time and rate measures of behavior under conditions of changing preference. Experiment 1 studied a concurrent chain schedule with random-interval initial links and fixed-interval terminal links; Experiment 2 studied a multiple chained random-interval fixed-interval schedule; and Experiment 3 studied simple concurrent random-interval random-interval schedules. In Experiment 1, and to a lesser extent in the other two experiments, session-average initial-link wait-time differences were linearly related to session-average response-rate differences. In Experiment 1, and to a lesser extent in Experiment 3, ratios of session-average initial-link wait times and response rates were related by a power function. The weaker relations between wait and response measures in Experiment 2 appear to be due to the absence of competition between responses. In Experiments 1 and 2, initial-link changes lagged behind terminal-link changes. These findings may have implications for the relations between fixed- and variable-interval procedures and suggest that more attention should be paid to temporal measures in studies of free-operant choice.

Key words: choice, changeover time, interresponse time, interval schedules, conditioned reinforcement, wait time, key peck, pigeons

Organisms can be trained to choose between sources of primary reinforcers (concurrent schedules) or between stimuli that signal the occurrence of primary reinforcers (concurrent chain schedules). In terms of response- and reinforcer-rate measures taken across sessions, results from concurrent schedules are relatively straightforward: In the steady state, relative response rate approximately matches relative (primary) reinforcer rate, the well-known matching law (Herrnstein, 1961, 1997; see review in Davison & McCarthy, 1988). The results with concurrent chain schedules are more complex, and several theories have been proposed, such as a version of the matching law (Herrnstein, 1964), delay-reduction theory (Fantino, 1969), context theory (Grace, 1994), incentive theory (Killeen, 1982; Killeen & Fantino, 1990), and hyperbolic value-addition (Mazur, 1997, 2001; reviews in Williams, 1988, 1994). But there is not yet consensus on the best theory of steady-state concurrent-chain choice.

The emphasis on cross-sessions, average-rate variables has meant that most concur-

rent-chain experiments have used variable- or random-interval (VI or RI) schedules (usually of equal value) in the initial link, rather than fixed-interval (FI) or fixed-ratio schedules, because of the steady responding they usually generate. Pausing, however, is often observed in VI initial links in concurrent chain schedules when the terminal links are fixed intervals (Shull & Spear, 1987), and the data of Shull, Gaynor and Grimes (2001) suggest that molar response rate may not capture what is occurring even on simple VI schedules. Perhaps additional light can be shed on the still unresolved problem of an adequate general theory for steady-state choice behavior in pigeons by looking at time as well as rate measures and at transitions as well as steady states. Previous experiments on transition behavior have primarily explored the rate of behavior change with little attention paid to the temporal elements of response rate (e.g., Bailey & Mazur, 1990; Dreyfus, 1991; Grace, 2002a; Horner, Staddon, & Lozano, 1997; Mazur, 1992). In the present experiments, we explored a range of dependent measures (both time and response rate) on a session-by-session basis in concurrent, concurrent chain, and multiple chain schedules. The principal reason for using these particular procedures was to explore the generality of our findings in ostensibly different procedures. We studied three related procedures: concurrent chain schedules with equal RI initial links and

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FI terminal links (Experiment 1), multiple chain RI FI (Experiment 2), and simple concurrent RI RI schedules (Experiment 3). The method in all three experiments was the same. We trained pigeons on these schedules with one alternative (Experiments 1 and 3) or component (Experiment 2) associated with a shorter overall time to food reinforcement than the other alternative or component. After a few sessions, the schedules were reversed. This procedure was repeated two or more times. We measured the time of occurrence of every event in each session of each experiment and assessed the covariation among rate and time measures as preference changed after each transition.

EXPERIMENT 1: CONCURRENT CHAIN RI FI

In Experiment 1 we arranged a two-link concurrent chain schedule with RI initial links and FI terminal links. The initial links were identical RI 40-s schedules on two side-by-side response keys. Responses to these initial links produced either short (FI 15-s) or long (FI 45-s) terminal links, a condition known to produce steady-state relative initial-link response rates that are more extreme than terminal-link relative reinforcer rates (Fantino, 1969; Killeen, 1970; Wardlaw & Davison, 1974): that is, greater than 3:1 preference for the FI 15-s alternative. The locations of the short and long terminal links were switched after varying periods of exposure. The only criterion for switching was that behavior showed some change since the last switch.

Experiment 1 addressed the following questions: (a) Are the effects of changes in terminal-link delay only on initial-link response rates or are temporal measures such as wait time and changeover time (defined below) also affected? (b) How are the different dependent measures related? (c) Do pigeons behave differently following primary reinforcers obtained for left and right responses or are all reinforcers treated similarly? (d) Do initial- and terminal-link measures change together, or do performance changes in the terminal links precede those in the initial links?

METHOD

Subjects

Three White Carneau pigeons, 2 males (P38 and P7380), and 1 female (P6381), were maintained at about 85% of their free-feeding weights. They received free access to water in their home cages. The pigeons were housed in individual cages in a room with a 12:12 hr light/dark cycle. All pigeons had previous experience in studies on matching-to-sample, transitive inference, and choice (Cleaveland, 1998).

Apparatus

Pigeon chambers were constructed from plastic 24-gal (90.84 L) storage containers, 370 mm wide, 460 mm long, and 310 mm high. A plastic grid floor provided secure footing. Access to a touchscreen-equipped computer monitor was provided by a 270 mm wide by 200 mm high opening in one end of the container. The bottom edge of the touchscreen was 80 mm from the floor. Reinforcers consisting of mixed grain were delivered through a feeder opening located on the right wall, 75 mm from the floor and 105 mm in front of the screen. An exhaust fan on the wall opposite the screen circulated air and provided masking noise.

Stimuli were presented on a 13 in. (33.02 cm) VGA monitor equipped with a Carroll Touch Technology® (Elo TouchSystems, Inc.) 13 in. (33.02 cm) infrared (IR) touchscreen. Pecks to stimuli were cushioned by a flexible 1-mm clear plastic sheet placed 5 mm in front of the monitor surface. Effective pecks, breaking the IR beams and making contact with the clear plastic, brought the pigeons' corneas 40 mm (± 2 mm) from the monitor. The maximum x - y resolution of the touchscreen was 3.15 mm on both axes; responses were sampled 40 times per second. Software recorded a peck to a stimulus at the termination of a touchscreen response; that is, when the beak broke the IR beams and was removed. Because of the resolution of the IR grid, responses were recorded in a circular area slightly larger than the stimulus disk that varied in diameter between 25.2 and 23.5 mm. Only responses that started and ended within the recording area were counted.

We recorded all event times throughout, including postreinforcement pausing in the

initial links and times between terminal-link entry and the first peck (terminal-link waiting), and interresponse times (IRTs) and changeover times (i.e., time between the last response to one key and the first response on the other) in the initial links.

Procedure

Despite previous experience in standard pigeon chambers, the pigeons did not immediately peck the touch screen. Pecking was established by autoshaping to stimuli presented on the computer monitor. In these sessions, a 30-s intertrial interval ended with the presentation of a 20-mm white disk for 5 s in the middle of the touch screen, followed by food for 3 s.

Concurrent-chains sessions (Figure 1) began after the pigeons showed reliable responding in the autoshaping procedure. *Initial links* were arranged on two horizontally displayed white disks, 20 mm in diameter, 90 mm apart and 150 mm from the floor. *Terminal links* were arranged on two disks, 20 mm in diameter, 180 mm apart and 250 mm from the floor. The left terminal link was green and the right terminal link was yellow. The initial-link schedules consisted of independent RI 40-s schedules arranged by sampling a probability gate set at $p = .025$ every second. No initial-link changeover contingencies were in effect. Sessions ended after 50 min of initial links. Little postsession feeding was required to maintain the pigeons at their 85% weight.

When an initial-link response produced the appropriate terminal-link stimulus, initial-link stimuli disappeared. The terminal links were simple FI schedules. The reinforcer was 2.5-s operation of a pigeon feeder containing mixed grain, during which the feeder was lit and the stimulus display was darkened. Offset of feeder operation was followed immediately by a return to the initial link.

Pigeons were initially exposed to equal FI 45-s terminal links for several sessions. Terminal-link contingencies were then changed midsession to FI 15 s and FI 45 s. Additional reversals in terminal-link contingencies, in which the left and right durations of the FI schedules were swapped, were arranged midsession after varying numbers of sessions. Changes in terminal links were made without concern for stability of behavior. Some chang-

es were made after only a few sessions, but we occasionally permitted preference for the FI 15-s terminal link to shift to extreme values when the FI-45 s terminal link was rarely visited. In general, conditions were changed only after some change in preference had been observed in the current condition but before choice proportions had reached fixation on the shorter alternative. The sequence and duration of conditions for individual pigeons are shown in Table 1.

Measures

The usual dependent variables in concurrent-chain experiments are response rates in the initial links, and the usual independent variables are the rates of primary reinforcers in the terminal links, both measured across several daily sessions. Theoretical analyses usually refer to relative (proportions or ratios) response and reinforcer rates. Our independent variables were the two terminal-link FI values, but we also looked at a number of dependent measures in addition to rate, measured in individual sessions or half sessions.

The different initial-link measures are explained in Figure 2, which shows a typical sequence of events in the initial link after its onset (signaled by the end of food reinforcer delivery) and the reappearance of the two initial-link key stimuli. Initial-link offset (not shown) is signaled by the disappearance of the two choice stimuli and the appearance of the chosen single-key terminal-link stimulus. The initial-link measures we examined included postreinforcement *wait times*, WT_L and WT_R , (times to the first response, sometimes also called response latency) in the two initial links. The wait time to the first response to either initial-link key (i.e., the shorter wait time, WT_L in Figure 2) we termed the *postreinforcement pause*. If no response occurred on a side in a given initial link, wait time for that side during that cycle was set equal to the link duration. Additional measures were: (a) the times between the last response on one alternative to the next response on the other alternative, *changeover time*: CO_{LR} and CO_{RL} ; (b) the times between successive responses in the left and right initial links, *interresponse time*: IRT_L and IRT_R ; and (c) the total number (per cycle and per session) of initial-link responses in the left

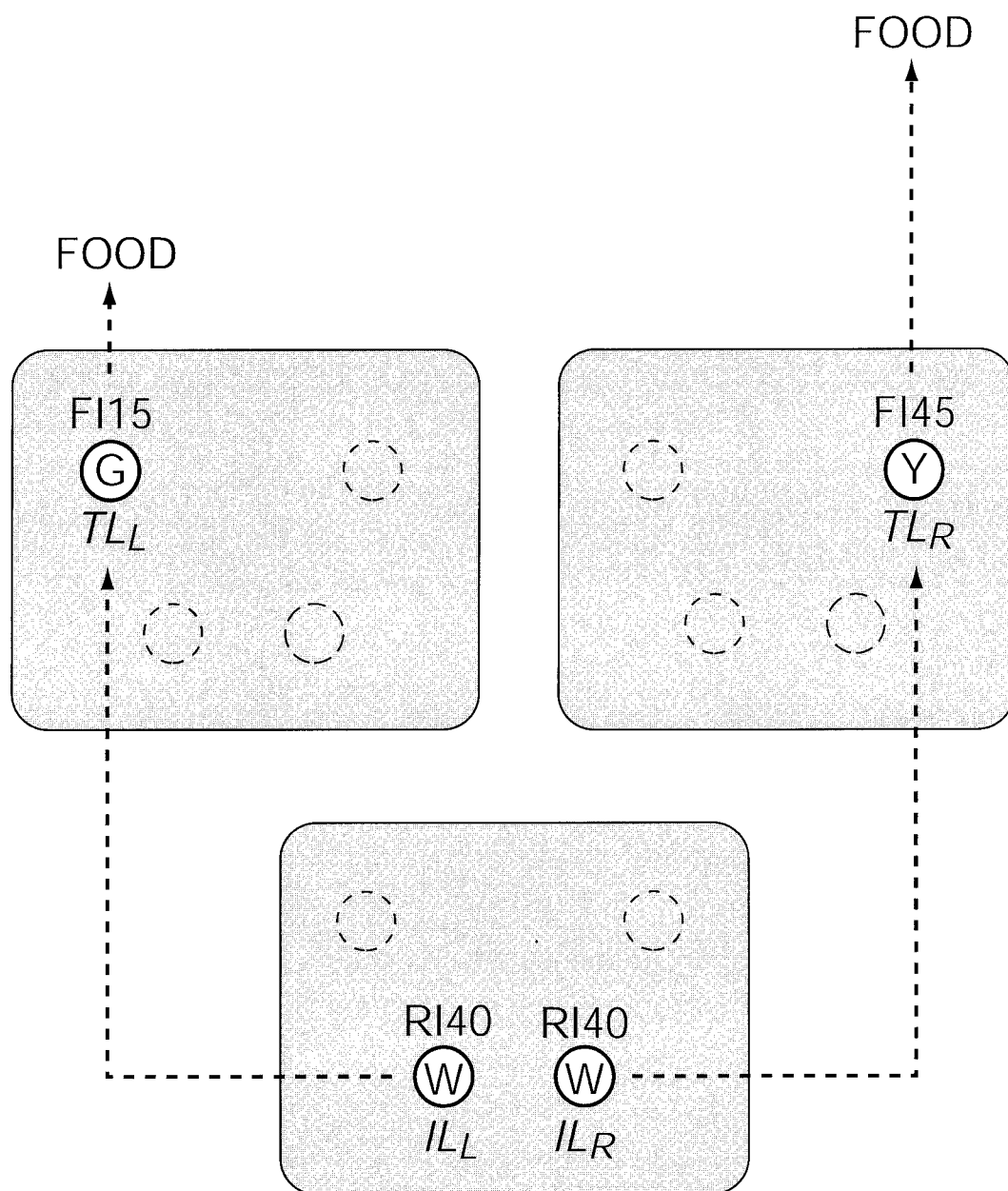


Fig. 1. Schematic diagram of the concurrent-chain procedure in Experiment 1. The lower gray rectangle shows the computer stimulus display during the white (W) initial links (IL_L and IL_R). Pecks in the left initial link produced the green (G) left terminal link (TL_L) according to an RI 40-s schedule; pecks on G produced food according to an FI 15-s schedule. Pecks on the right initial link produced the yellow (Y) right terminal link (TL_R) according to another RI 40-s schedule; pecks on Y produced food according to an FI 45-s schedule. Initial-link stimuli disappeared during terminal links (dashed circles); the entire screen was darkened during feeder deliveries; and initial links reappeared immediately after food deliveries. The FI 15-s and FI 45-s terminal links alternated between left and right over sessions whereas stimulus colors and positions remained fixed (see text for details).

Table 1

Session numbers in which various concurrent-chain terminal-link conditions were arranged on the left and right alternatives in Experiment 1.

Pigeon	FI 45 s, FI 45 s	FI 15 s, FI 45 s	FI 45 s, FI 15 s
7380	1-4	5-6, 16-29, 46-66	7-15, 30-45, 67-79
38	1-17	31-54, 80-92	18-30, 55-79
6381	1-11	12-26, 42-64	27-41, 65-74

and right initial links, N_L and N_R , which is a measure of *response rate* given that both initial links are present for an equal amount of time in each session.

We also measured wait times in the two terminal links, following the onset of the two terminal-link stimuli, and postwait-time rate (*running rate*) and response rate in the terminal links (responses divided by terminal-link duration).

The initial-link measures described above are not totally independent of one another. For example, the longer the wait time, the less time available for responding and (other things being equal) the lower the number of responses made. Total time of exposure to

left and right choices during the initial link is necessarily the same, because both initial-link stimuli are always present together. This initial-link time can be partitioned into the time before the first response on a given side, WT_L or WT_R , and the time after the first response, which will usually contain additional responses. Postwait-time responding on a given side may be interrupted by switches to the other side (changeovers), as shown in Figure 2 for the left initial link. Changeovers in either direction subtract equally from the time available for responding on both keys. Let us suppose that the number of postwait-time responses on each side, N_L and N_R , is proportional to the time available for them; that is,

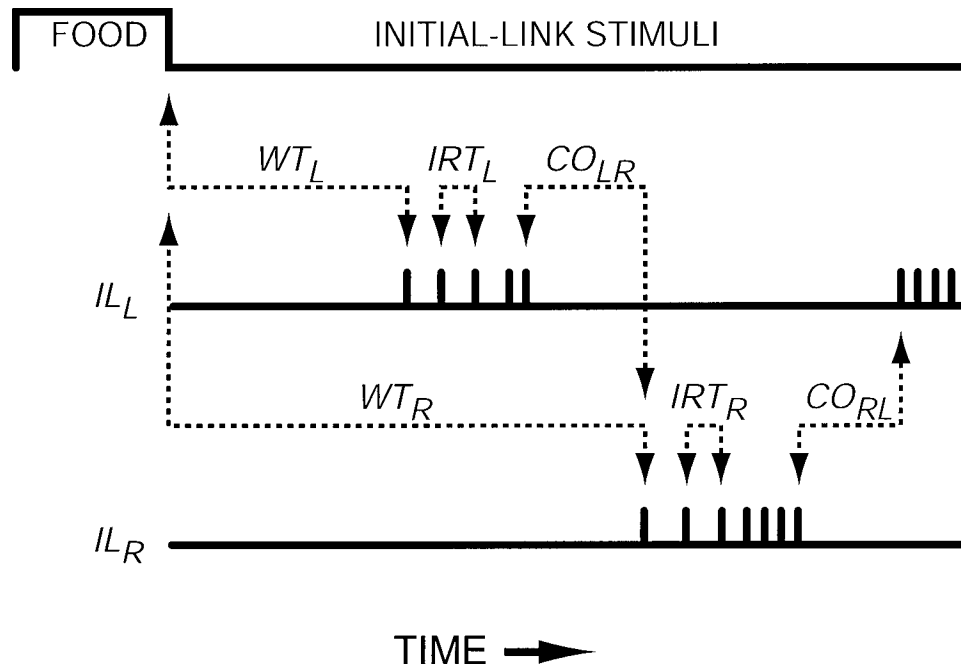


Fig. 2. Temporal properties of responses on left (IL_L) and right (IL_R) initial-link stimuli of the concurrent-chain procedure in Experiment 1. In this example, the first response following food occurs on IL_L , with left wait time WT_L ; four left responses that follow provide four IRTs, IRT_L (for clarity, only one IRT is labeled). Next is a changeover to IL_R with a changeover time CO_{LR} , and right wait time WT_R . Six right responses follow at six right IRTs, IRT_R ; finally, there is a changeover to the next response on IL_L , after a changeover time CO_{RL} .

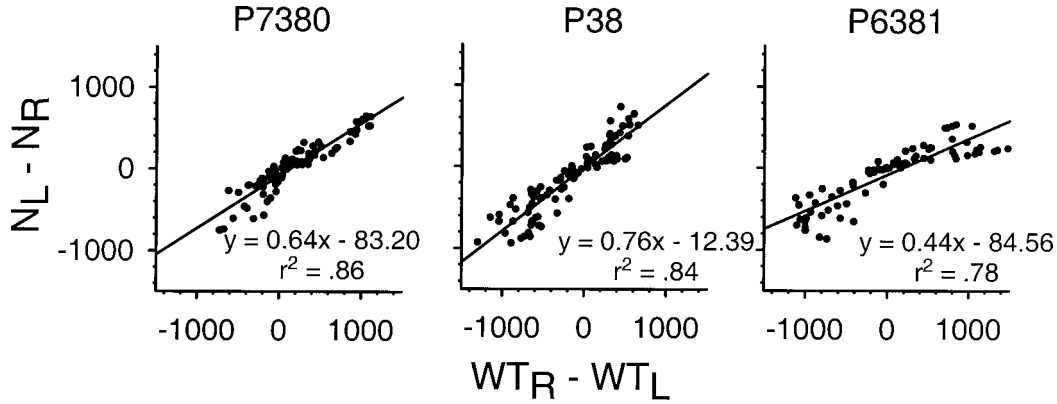


Fig. 3. Scatter plots of $\Sigma N_L - \Sigma N_R$ versus $\Sigma WTR - \Sigma WTL$ for the 3 pigeons in Experiment 1 (see Equations 2 and 3. Σ s are omitted for simplicity in the axis labels.). N_L and N_R are the total number of left and right initial-link responses in a session, and WTL and WTR are the corresponding total initial-link wait times to the first response (details in text and in Figure 2). If no response occurred on an alternative, wait time is the time between the end of food delivery and terminal-link onset. Each point represents data from an entire session, and all sessions in Experiment 1 are shown. Best-fitting linear functions and r^2 values shown on plots were calculated using structural equations models and maximum-likelihood estimation methods.

to total time (initial-link duration) less wait time and changeover time. This would mean that, in each presentation of an initial link (each schedule *cycle*), initial-link time, D , on either alternative is made up of wait time, plus changeover (in either direction) time, plus a time proportional to the number of IRTs on that side; that is, $D_L = WTL + CO + \alpha_L (N_L - 1)$, where α is the mean IRT for responses on the left. For an entire session, therefore,

$$\sum D_L = \sum WTL + \sum CO + \alpha_L \sum (N_L - 1), \quad (1a)$$

and similarly for the right side,

$$\sum D_R = \sum WTR + \sum CO + \alpha_R \sum (N_R - 1), \quad (1b)$$

But $\sum D_L = \sum D_R$, because both initial-link keys are always available at the same time. If mean IRT is the same for both choices ($\alpha_L = \alpha_R = \alpha$), then equating Equations 1a and 1b yields a particularly simple result:

$$\sum N_L - \sum N_R = \frac{\sum WTR - \sum WTL}{\alpha}. \quad (2a)$$

Omitting the Σ s for simplicity, and using N and WT for session-total values, Equation 2a can be rewritten,

$$N_L - N_R = \frac{WTR - WTL}{\alpha}. \quad (2b)$$

Equation 2 implies a linear relation between the difference between the total number of initial-link responses on left and right versus the difference between the sums of wait times on right and left. This relation has a zero intercept and slope equal to $1/\alpha$, where α is mean IRT. We looked for this simple relation in the data.

RESULTS

Figure 3 shows the relation between daily values of $N_L - N_R$ and $WTR - WTL$ across the whole experiment for the 3 pigeons (the sequence of conditions is shown in Table 1). There was an approximately linear relation in each case, with squared correlations (r^2) between the two variables of .78 or more (all correlations were calculated using structural equations models and maximum-likelihood estimation methods with SAS Institute, Inc. programs (see discussion in Isaac, 1970). The intercepts of fitted lines were small in relation to the data range, but were significantly less than zero ($p < .05$).

The linear relation shown in Figure 3 is generally consistent with the assumption that initial-link mean IRT is constant. There is another close relation between wait time and overall response rate, illustrated in Figure 4, which shows initial-link wait-time ratios (WTR/WTL), changeover-time ratios (CO_R/CO_L), and IRT ratios (IRT_R/IRT_L) plotted

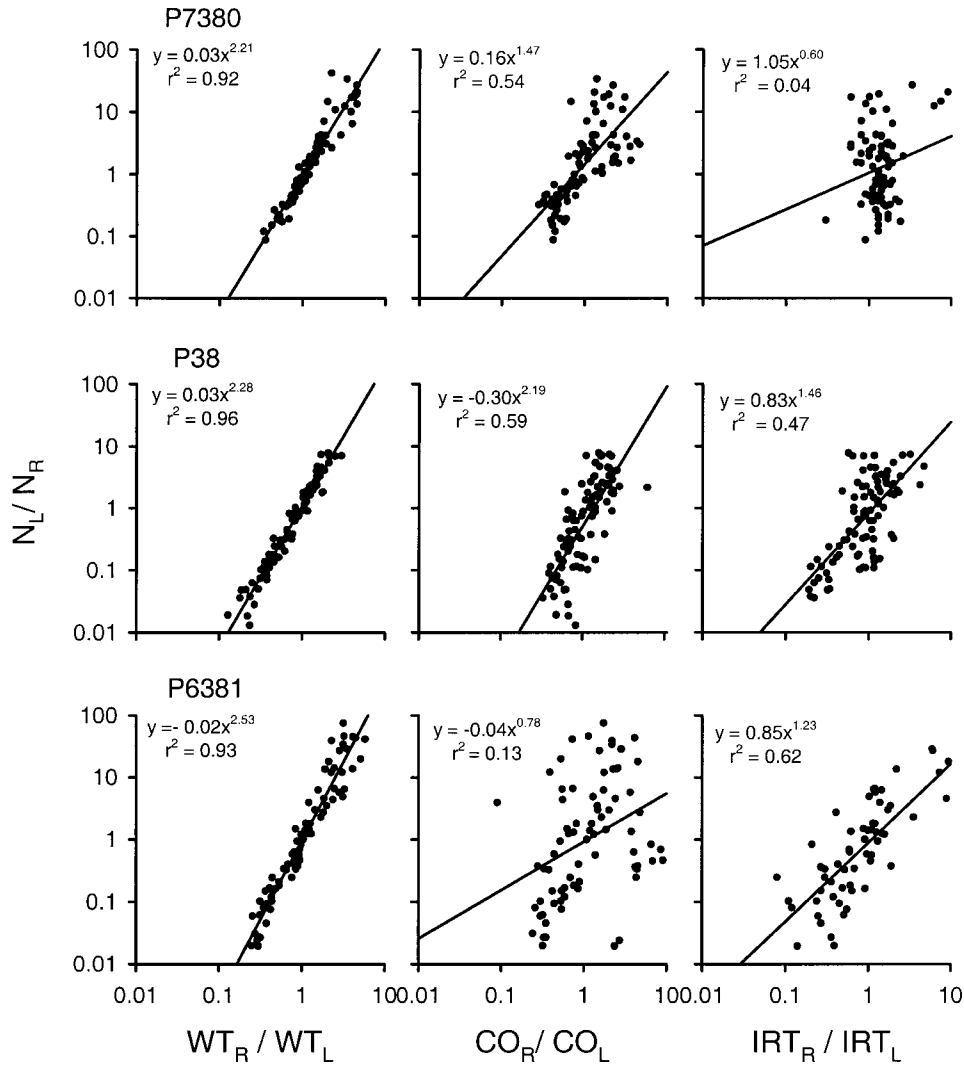


Fig. 4. Scatter plots of session-average relative response rates (N_L/N_R) versus relative wait times (W_{T_R}/W_{T_L}), changeover times (C_{O_R}/C_{O_L}), and IRTs ($I_{R_T_R}/I_{R_T_L}$) in Experiment 1 (details in text; also see Figure 2). All axes are logarithmic. Best-fitting linear functions and r^2 values shown on plots were calculated using structural equations models and maximum-likelihood estimation methods. Other details as in Figure 3.

against initial-link response-rate ratios (N_L/N_R), all on log-log coordinates. The closest relation was between response-rate ratios and wait-time ratios (left column: squared correlations of .92 or greater). There were weaker correlations between response-rate ratios and changeover-time ratios (middle column: squared correlations of .59 or less) and between response-rate ratios and IRT ratios (right column: squared correlations of .62 or less).

The correlation between *absolute* wait time

and response rate was much weaker than between wait-time and response-rate *ratios*. For example, the squared correlation between N_L and $1/W_{T_L}$ ranged from .28 to .68 (and between N_R and $1/W_{T_R}$ from .42 to .67), compared to squared correlations greater than .92 between wait-time ratios and response-rate ratios.

Although the linear relation in Figure 3 suggests a uniform mean IRT, session-average plots of running rate ($1/\alpha$), defined according to Equation 1, were in fact far from con-

stant. Daily plots showed that in general, IRTs were shorter in the initial link corresponding to the longer terminal link than in the initial link corresponding to the shorter terminal link. The negative relations in Figure 4 between response-rate and (inverse) IRT ratios for Pigeons P38 and P6381 are largely due to a higher ratio of short-to-long IRTs on the FI 45-s alternative. Figure 5 shows this directly with log-survivor plots (Shull, Gaynor, & Grimes, 2001) of proportions of IRTs on initial links corresponding to both FI 15-s and FI 45-s terminal links. FI 45-s plots show the fewest numbers of responses and the largest difference between short IRTs of less than 0.5 s on the FI 15-s link and the remaining IRTs. The pattern is most pronounced for Pigeon P6381, in which responding on the FI 15-s alternative was an extended mix of short and long IRTs, whereas responding in the FI 45-s alternative comprised a few visits made up of short duration IRTs (Baum, Schwendiman, & Bell, 1999). Nevertheless, there is probably little significance of the inconstancy we found in $1/\alpha$ for Equation 1 because the most extreme differences in short-to-long IRT durations occurred on the FI 45-s schedule and involved sessions with very few responses on that alternative (see Figure 5 and top panel of Figure 8).

Absolute IRTs showed a slow decrease as the experiment progressed (i.e., the pigeons pecked faster overall), and by the end of each condition, 2 of the 3 pigeons (P38 and P6381) showed a consistent difference between initial-link IRTs on the FI 15-s and FI 45-s keys.

The above analyses averaged wait times following reinforcers for left (L) and right (R) responses, treating all reinforcers as equivalent. But it is possible that animals waited a shorter time to respond on the left alternative following a reinforcer for a left response (LL waits) than following a reinforcer for an R response (RL waits), or vice versa. Figure 6 shows average (per session) wait time for the first initial-link response (postreinforcement pause, e.g., WT_L in Figure 2) sorted according to whether the previous reinforcer was for an L or R terminal-link response. Thus the left column shows scatter plots of wait times on the left initial-link key after reinforcement on left versus right, and the right column shows the same thing for waits on the right

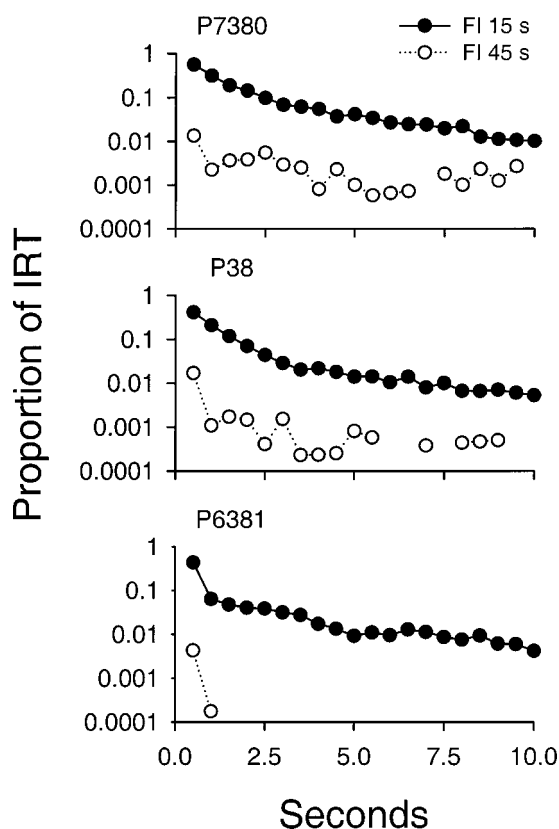


Fig. 5. Log-survivor plots of IRT frequencies on initial links of Experiment 1. IRT bins are 0.5-s intervals. Points in each plot show the proportion (on a log scale) of IRTs on both FI 15-s and FI 45-s initial links that are longer than a given duration, plotted as a function of elapsed time. Points are sums of data from the last three sessions in each reversal, summed over reversals. Intervals without data points indicate the absence of IRTs.

initial-link key. On the left key, wait time following left reinforcers was shorter than wait time following right reinforcers, and vice versa, for 2 of the 3 pigeons (P38 and P6381), but the group average was not reliably different, $t(2) = 4.2$, $p = .052$ (one-tailed paired t test). This is a difficult finding to interpret at this time because the effect is small (slopes are all close to 1.0 and the intercepts close to zero) and inconsistent.

Session-by-session analysis (not shown) confirms the scatter plots: When wait times were relatively stable from session to session, postreinforcement pauses on L or R were much the same whether the reinforcement was received for an L or R response. But occasionally, when wait time was variable (usually

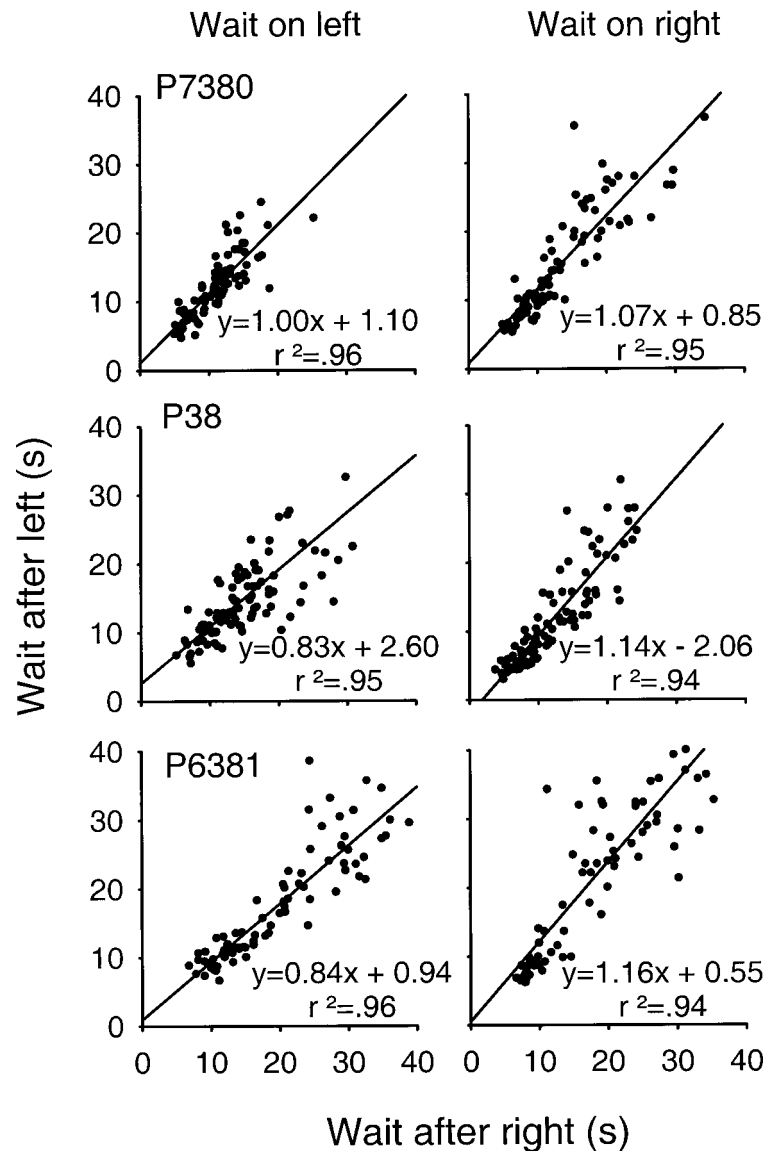


Fig. 6. Scatter plots of session-average initial-link wait times on left and right keys (columns) in Experiment 1. Wait times following a reinforced right-key response (x axis) are plotted against wait times following a reinforced left-key response (y axes). Best-fitting linear functions and r^2 values shown on plots were calculated using structural equations models and maximum-likelihood estimation methods.

when the sample size on one side was small), the two differed. Response rate, like wait time, was essentially the same after L and R reinforcers.

Effects of Terminal-Link Changes

Figure 7 shows the effects on initial-link and terminal-link response ratios and wait times of reversing the terminal-link schedules

every few sessions. Both ordinates are logarithmic; response-rate ratios on the left, wait-time ratios on the right. The figure illustrates four effects: (a) As was already apparent in Figure 4, initial-link response-rate ratios varied more widely in response to changes in terminal-link delays than did wait-time ratios; (b) although initial-link response-rate and wait-time ratios covaried almost exactly ses-

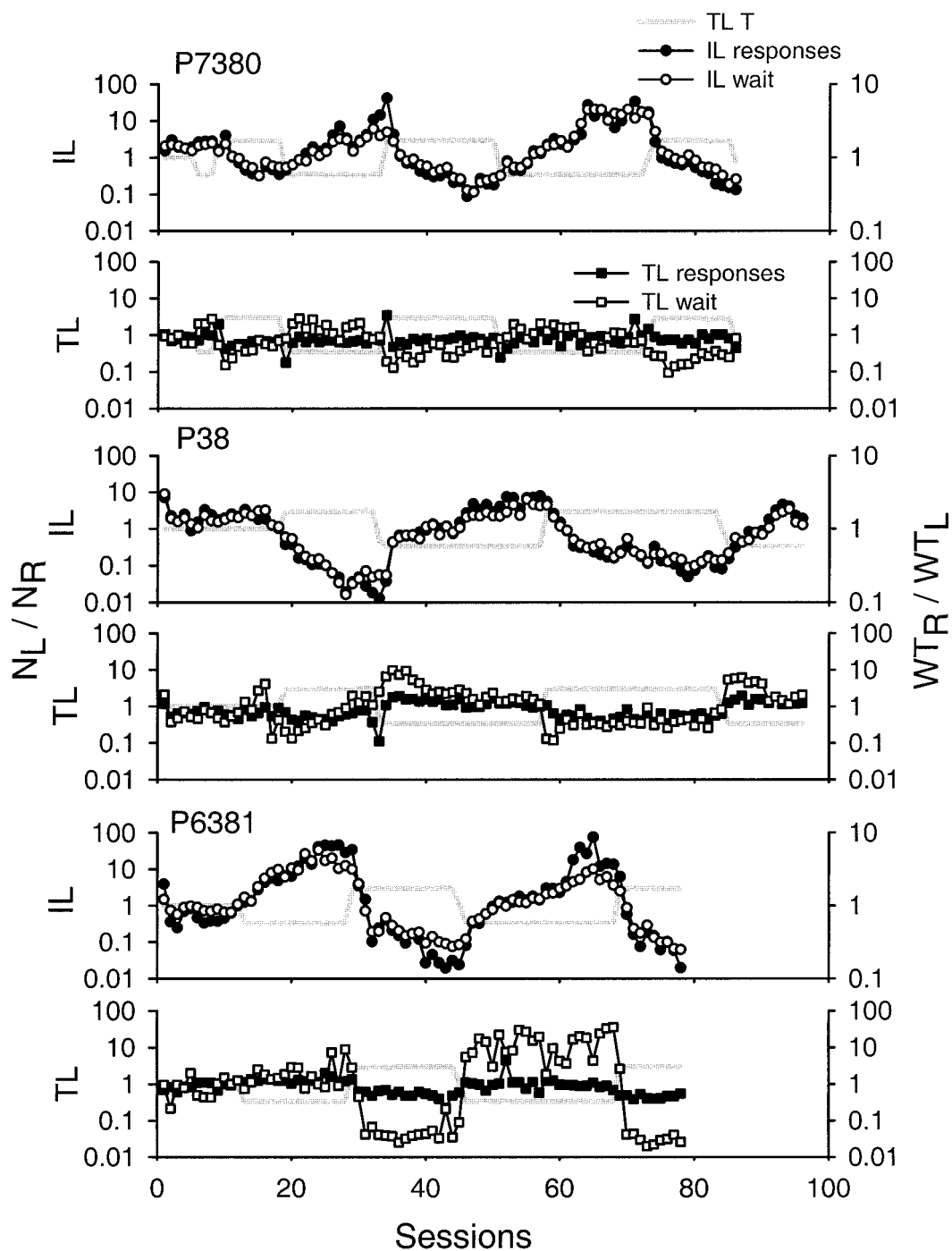


Fig. 7. Plots on log coordinates showing session averages of initial- and terminal-link ratios of response rates (N_L/N_R) and wait times (WT_R/WT_L) in Experiment 1. Thick gray lines are obtained relative delays to reinforcement, TL_R/TL_L .

sion-by-session (also seen in Figure 4), this covariation was *not* true of the terminal link; (c) terminal-link response-rate ratios varied much less than terminal-link wait-time ratios; and (d) terminal-link measures followed schedule changes (i.e., reversals of terminal-link delays) more rapidly than initial-link measures.

Effect (d), above, is summarized in Figure 8, which shows the average effects of transitions between FI 15 s on the left and FI 45 s on the right to FI 45 s on the left and FI 15 s on the right (left column) and the reverse (right column) on initial-link and terminal-link response rates and wait times. Terminal-link measures changed within two sessions following the shift, but initial-link measures did not seem to reach asymptote even after eight sessions. Session-by-session cross-lag correlations between initial- and terminal-link wait and response measures confirmed the lags in initial-link changes following adjustments in terminal-link wait and response measures (shown in Figure 8), and also found that initial-link responses and waits (shown in Figure 7) changed simultaneously in the same session.

The results shown in Figures 3 and 4 were sufficiently striking that we felt it necessary to repeat this experiment with Pigeons P7380 and P38 from the original experiment and a new pigeon, P1348. The replication was conducted after completing Experiment 3 plus a concurrent-chain FI FI experiment (not reported here). The results were similar: substantial correlations between response-rate and wait-time differences (as in Figure 3), and between response-rate and wait-time ratios (as in Figure 4).

DISCUSSION

The strategy in Experiment 1 was to alter-nate the unequal FI schedules in the terminal links of the concurrent chain schedule between left and right alternatives and to look at the effect on various measures of behavior in initial and terminal links as they changed across sessions. We found three new regularities: (a) Wait-time differences and response-rate differences were linearly related (Equation 2 and Figure 3); (b) the ratios of session-average initial-link response rates and the inverse ratio of initial-link wait times were

related by a power function with exponent 2.2 or greater; that is, the range of wait-time variation was less than the range of response-rate variation (Figure 4, left panels); and (c) changeover-time ratios and to some extent, interresponse-time ratios, showed a similar, but weaker, relation to response ratios (Figure 4, center and right panels).

The linear relation between initial-link wait-time and response-rate differences is consistent with the hypothesis that initial-link running rate ($1/\alpha$) is constant. There are, however, two discordant features in Figure 3: a significantly nonzero intercept, and some suggestion of nonlinearity in the scatter plots. The suggestion of nonlinearity is perhaps attributable to changes in α corresponding to the changes in mean IRT across conditions visible in daily plots (not shown). We have done simulations (not presented here) that show that in fact the linear relation in Figure 3 is quite robust and under many conditions will appear even if running rate ($1/\alpha$) is a nonlinear function of wait time. The conclusion seems to be that although IRTs on both sides vary over as much as a 10:1 range, the range of variation of response-rate and wait-time differences is much greater: from -1000 to $+1000$ (Equation 2 and Figure 3), so that Equation 1 is sufficient to yield the correlations in Figure 3.

We are not certain of the reason for the range difference between wait-time and response-rate ratios visible in Figure 4, but a possible interpretation is as follows. Overall response rates, N_L and N_R , are affected by both wait time and changeover time because, as these times increase, time available for responding decreases. Wait time subtracts from the time available to that response only; a left response may occur during the wait time on the right and vice versa. But changeover times in either direction subtract equally from the time available for both responses. If mean IRT is constant, it follows that

$$N_L = \frac{(D_L - WT_L - CO)}{\alpha} \quad (3)$$

and similarly for the other response—where α is a constant equal to mean IRT and CO is the sum of changeovers in both directions (this is simply Equation 1a rewritten and simplified). It is easy to show by simulation that

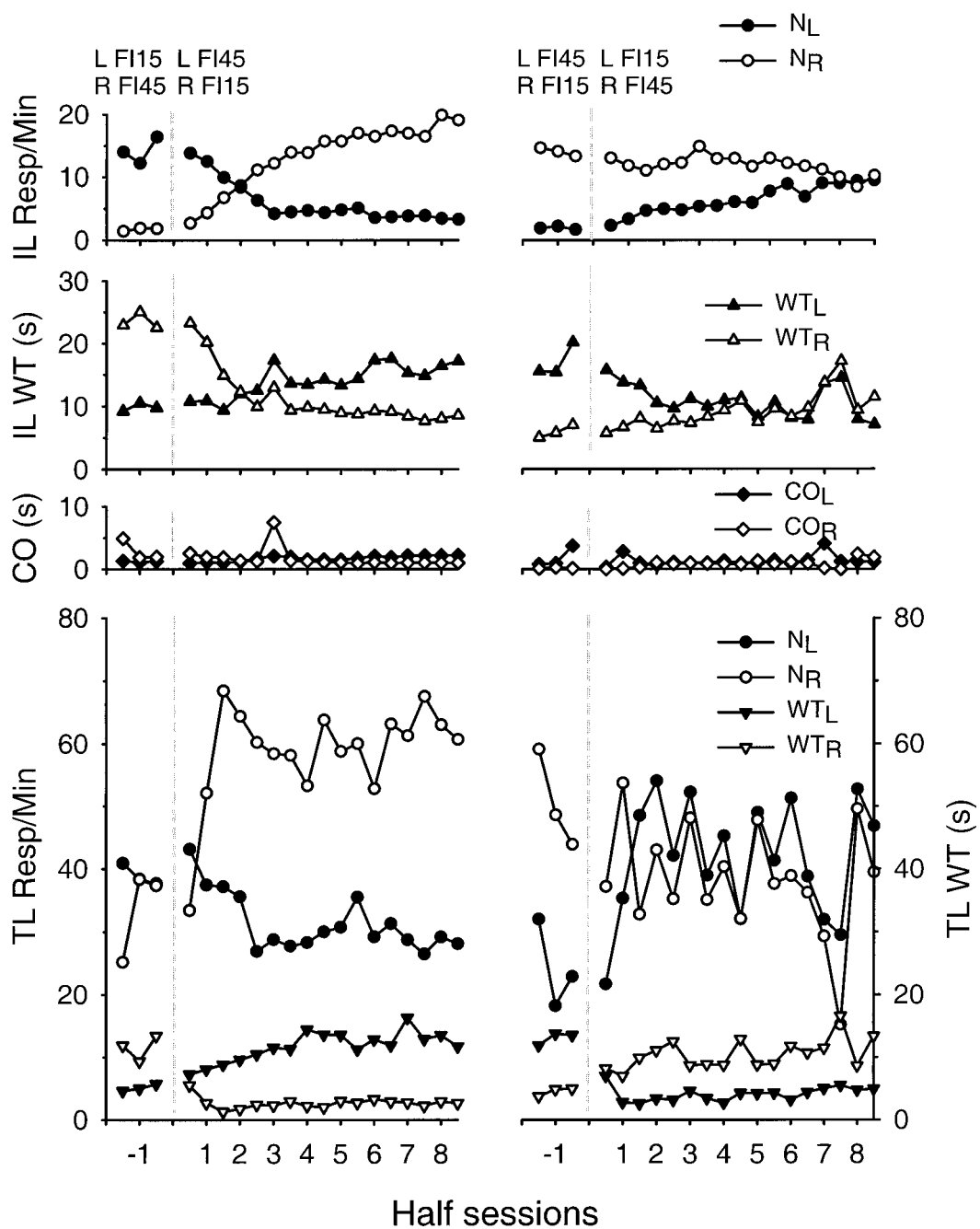


Fig. 8. Initial- and terminal-link wait times, response rates, and changeovers before and after terminal-link reversals in Experiment 1. The left panels show TL reversals from left FI 15 s to FI 45 s, and right FI 45 s to FI 15 s; right panels show the opposite reversal. Data points represent half-session averages over all TL reversals and Pigeons P7380, P38, and P6381.

if WT varies in a complementary fashion on the two sides, and CO is a constant, then the log ratio N_L/N_R will be an approximately linear function of the log ratio WT_R/WT_L . Moreover, if the absolute values of $WT + CO$ are moderately large—but well within the observed range—the range of variation of N_L/N_R will be greater than the range of WT_R/WT_L . Thus ratios of N may show a greater range of variation than wait-time ratios, even though WT may be the true dependent variable, given only the assumption that when the pigeon begins to respond (during the times left after waiting and changeovers), it continues at the same constant rate on both sides.

The covariation of wait-time and response-rate ratios did not hold for the terminal links (Figure 8). Wait time was sensitive to time-to-reinforcement in both links, but response rate was sensitive to time-to-reinforcement only in the initial link.

The data show little evidence for the control of initial-link preference by the locus of the immediately preceding terminal-link reinforcement (Figure 6). Davison and Baum (2000, 2002) report an identifiable increase in preference for the side of the last reinforcer in concurrent VI VI schedules. In the case of concurrent chain schedules with independent initial links, as in the present study, Fantino and Royalty (1987) and Killeen (1970) found a greater proportion of responses on the side opposite the last reinforcer. But given the many procedural differences between the present study and those studies, we cannot be sure which variables are critical for the differing results.

Although it made little difference to either choice or wait-time measures whether the just-preceding reinforcer was for a left or a right response, we found that initial-link wait time was sensitive to changes in terminal-link delays (Figures 7 and 8). Taken together, these two results suggest that animals in this situation may be learning not so much “which initial-link key is better?” but “when should I respond (i.e., at what postreinforcement time) to the left or right alternative in the initial link?” Thus, after a terminal-link schedule switch from left FI 15 s, right FI 45 s to left FI 45 s, right FI 15 s, the animals learn to respond later on the left (longer WT_L) and sooner on the right (shorter WT_R), which translates into a shift in preference

from the left alternative to the right alternative.

The fact that initial-link responding changes when terminal-link schedules are reversed means that there must be *some* differential effect of left and right reinforcers on left and right responding. The effect may be to change the postreinforcement time at which left and right responses occur, to change the relative probability of left and right responses, or some other change. But these effects may be undetectable in this experiment given their speed, the existing level of variability, and the limited averaging possible with so few schedule changes.

Terminal-link measures responded to changes in the independent variable more rapidly than initial-link measures (Figures 7 and 8; Grace, 2002b). There are at least three simple interpretations of this difference: (a) Conditioned reinforcement—initial-link responding is determined by the conditioned reinforcement associated with the terminal link; hence initial-link measures cannot change until the animal has learned about the changed properties of the terminal link, (b) events closer in time to reinforcement are affected sooner than effects further away (like the “backward order of elimination of errors” in maze learning), and (c) initial-link time-to-reinforcement is variable whereas terminal-link time-to-reinforcement is fixed; hence pigeons must learn many more interval values in the first link. Experiment 1 does not distinguish among these possibilities, but the last alternative is most likely to the extent that wait time on each schedule component is determined by time-to-reinforcement.

Why is there covariation between wait-time and response-rate ratios (Figure 4)? There are at least two possible answers: (a) statistical covariation between rate and time measures, and (b) nonindependence of measures.

The first possibility is not interesting because it involves no psychological process. It can be illustrated as follows. If responding is random in time, at a rate x , then the average IRT will equal the average waiting time and both will equal $1/x$. Thus x (response rate) and $1/x$ (wait time) will be linearly related with unit slope, and response and wait-time ratios will also be related with unit slope. Initial-link responding in this experiment was far from random, consisting of a pause-re-

spond pattern, and the slope of the relation shown in Figure 4 was much less than 1—and linear only on log-log coordinates. The problem is that initial-link wait time in this experiment was much too long to be plausibly attributed to differences in IRTs between the alternatives. Average latencies were on the order of 10 to 20 s (Figure 8), which is consistent with average response rate on the order of three to six responses a minute, whereas actual response rates were considerably higher, on the order of 5 to 30 responses a minute—and local response rate ($1/\text{IRT}$) was higher still. Moreover, as noted in the Results section, the correlation between absolute response rate and wait time on each side was much smaller than the correlation between wait-time and response-rate ratios.

The second possibility is that response rate and wait time may be linked because response rate is necessarily related inversely to both wait time and changeover time. If wait time is long, less time is available for responding; hence (other things being equal) response rate (measured over the whole time, including wait time) will be low. The same holds for changeover time. But notice that the constraint imposed by changeovers is different from that imposed by wait time, because changeovers in *either* direction subtract from the time available for responding on *either* key (see Figure 2). Thus, although there is likely to be an inverse relation between CO_{LR} and N_L , there is also an inverse relation between CO_{LR} and N_R , and similarly for the inverse relation between CO_{RL} and N_R . Because variation in changeover times in either direction affects the time available for both responses, not simply the changed-away-from response as in the case of wait time, there is no necessary relation between changeover ratios and response ratios. Nevertheless, changeover ratios and response-rate ratios *are* related, albeit more weakly than wait-time and response-rate ratios (Figure 4). A possible conclusion, therefore, is that response rate, despite its high sensitivity to terminal-link schedule variation, is a derived variable and the true initial-link dependent variable may be time spent on a given key (or, equivalently, time spent away from a key—wait time).

Table 2

Session numbers in which various multiple-chain terminal-link conditions were arranged in Experiment 2.

Pigeon	FI 15 s, FI 45 s	FI 45 s, FI 15 s
7380	20–38, 63–76	1–19, 39–62
38	11–18, 42–63	1–10, 19–41, 64–80
6381	9–18, 26–35	1–8, 19–25, 36–48

EXPERIMENT 2: MULTIPLE CHAIN RI FI SCHEDULES

Experiment 2 was designed to find out if the simultaneous availability of two initial links (which implies some degree of response competition in the initial link) played a role in the regularities we found in Experiment 1. In this experiment, schedule parameters and key arrangements were identical to those in Experiment 1, but only one chain was available at a time, with left and right chains appearing equally often in a random sequence. The FI 15-s and FI 45-s terminal links were changed between the two sides every few sessions, as in Experiment 1. If initial-link response competition is irrelevant to concurrent-schedule performance, the results should be similar to those shown in Figures 3 and 4.

METHOD

The subjects and other procedural details such as positions of left and right initial- and terminal-link stimuli were the same as in Experiment 1, but the two chain components were presented separately, as just described. The random sequence of chains was determined by sampling without replacement in blocks of 10 trials. The numbers of sessions under the multiple-chain terminal-link conditions for the 3 pigeons are presented in Table 2. Sessions were terminated after 60 cycles, 30 on each side.

RESULTS

Equations 1 and 2 imply a linear relation between $N_L - N_R$ and $WT_R - WT_L$. The relevant plot for the multiple chain is shown in Figure 9. The squared correlations for the present experiment (.22 to .70) were smaller than in the concurrent-chain case (.78 to .86).

Wait-time ratios were only weakly related to response-rate ratios in the multiple schedules. Individual-subject squared correlations ranged

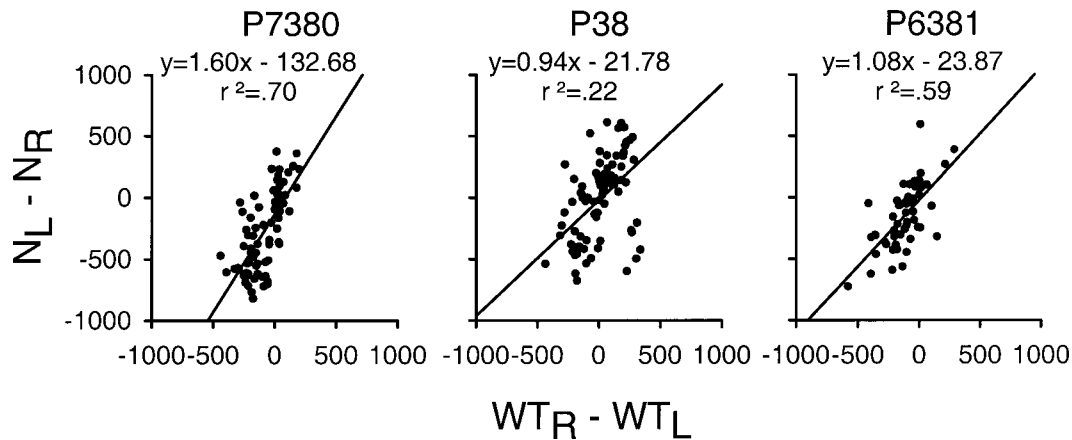


Fig. 9. Scatter plots of $N_L - N_R$ versus $WTR - WTL$ for subjects in Experiment 2 (details as in Figure 3). Best-fitting linear functions and r^2 values shown on plots were calculated using structural equations models and maximum-likelihood estimation methods.

from .11 to .70 in comparison with .92 to .96 in Experiment 1 (Figure 4). Unlike the case in Experiment 1, response ratio was weakly positively related to the ratio of mean IRTs (squared correlations from .12 to .49). In comparison with Experiment 1, the range of variation in the initial-link responses and wait time was less than in the concurrent-chain case.

Figure 10 shows initial-link wait times throughout the experiment, sorted according to the preceding terminal-link reinforcement (corresponding to Figure 6 in Experiment 1). The relations were much weaker than in the concurrent-chain case, and provided no evidence that wait time differed depending on the source of the previous reinforcer. Slopes of regression lines in the left and right panels averaged about 0.78 in both cases, indicating no differential effect of side of reinforcer but some tendency to respond sooner after left reinforcers over the course of the experiment.

Cross-lag correlations carried out on initial- and terminal-link measures found that the responses and wait time covaried more closely in the initial link than in the terminal link, and that initial-response-rate and wait-time ratios lagged behind changes in response and wait time adjustments in the terminal-link schedules. In the terminal links, wait-time ratio was generally more sensitive to changes in terminal-link duration than response ratio, as in Experiment 1.

DISCUSSION

The main conclusion from Experiment 2 is that the close relation between wait-time and response-rate differences (Figure 3) and, especially, between response-rate and wait-time ratios (Figure 4) in Experiment 1 was not maintained. Both these relations seem to depend on the fact that the animals had to choose between the two initial links in the concurrent-chain procedure of Experiment 1, but did not need to do so in Experiment 2, in which the links were presented separately. A corollary of this result is that the initial-link concurrent chain schedule performance is more sensitive to the effects of terminal-link delay than the single-RI schedule performance in simple chains, a conclusion consistent with the results of previous studies (Davison & McCarthy, 1988; Wardlaw & Davison, 1974; Williams, 1988).

Changes in initial-link dependent measures were delayed relative to changes in the terminal links, as in Experiment 1. Additionally, initial-link wait time and response rate varied less in response to changes in terminal-link reinforcement delay in this experiment than in Experiment 1.

EXPERIMENT 3: CONCURRENT RI RI SCHEDULES

Experiment 1 showed reliable covariation between initial-link response-rate ratios and

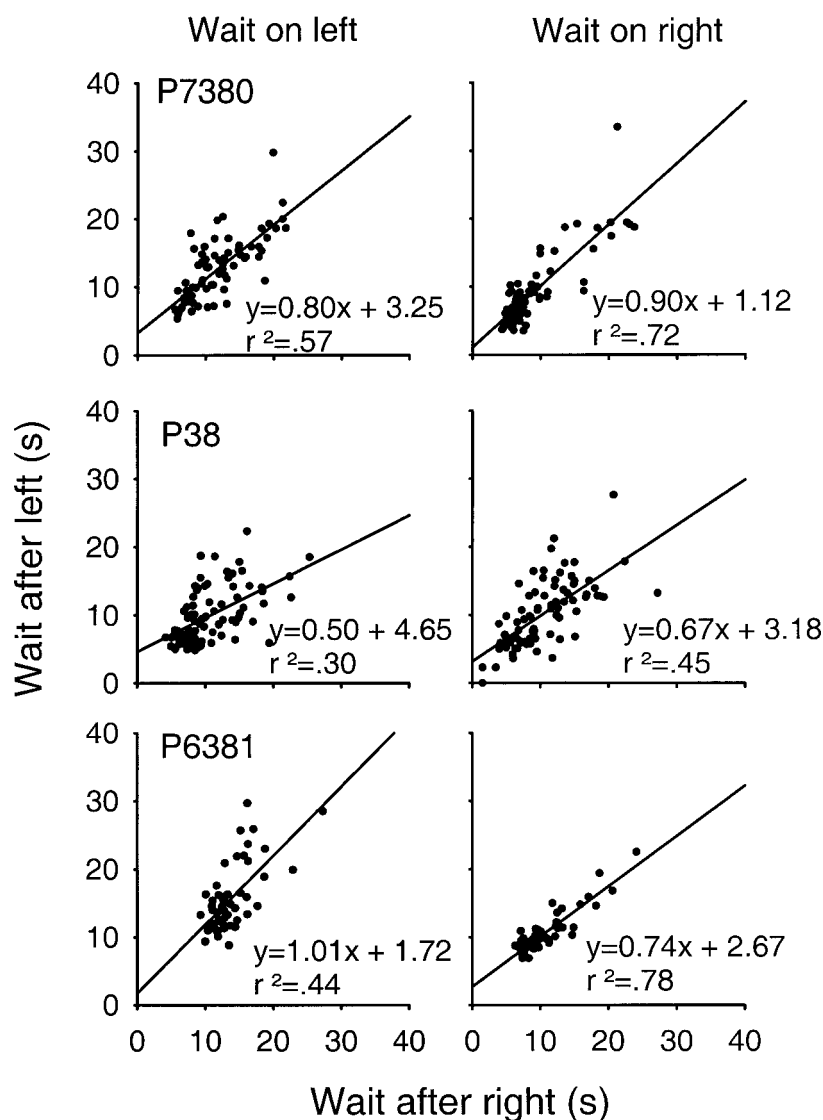


Fig. 10. Scatter plots of session-average initial-link wait times on left and right keys (columns) in Experiment 2. Wait times following a reinforced right-key response (x axis) are plotted against wait times following a reinforced left-key response (y axes). Best-fitting linear functions and r^2 values shown on plots were calculated using structural equations models and maximum-likelihood estimation methods.

wait-time ratios on a concurrent chain RI FI schedule. However, this covariation was not found in the terminal links. Was this difference because the terminal links are simple schedules whereas the initial links are links in a chain? Or was it because only the initial links were concurrent schedules? The latter seems more likely, given that we found little covariation in the multiple-chain procedure in Experiment 2. Experiment 1 also showed that session-average initial-link wait times and

response rates on the left and right choices were similar following reinforcers delivered for left and right responses. In Experiment 3, we looked to see if this was also true on a simple concurrent schedule.

METHOD

Subjects, Apparatus, and Procedure

Subjects were 3 pigeons, 1371, 4600, and 931, maintained at approximately 85% of

Table 3

Session numbers in which various concurrent schedule conditions were arranged for the left and right alternatives in Experiment 3.

Pigeon	RI 30 s, RI 30 s	RI 15 s, RI 45 s	RI 45 s, RI 15 s
1371	1-4	5-10, 36-49, 70-82	11-35, 50-69
931	1-4	11-23, 40-55, 73-90	5-10, 24-39, 56-72
4600	1-4	5-11, 27-36, 53-65	12-26, 37-52, 66-88

their free-feeding weights. All 3 had previously served in experiments on choice and matching-to-sample. The apparatus and general procedure were the same as in Experiment 1. The schedule was a simple concurrent RI 15-s RI 45-s schedule (probability gate sampled every second with $p = .067$ and $p = .022$ for the RI 15-s and RI 45-s schedules, respectively). The two values alternated every few days, as in the previous experiments (see Table 3 for the entire series for each pigeon). As in Experiment 1, the RI schedules were independent so that reinforcers could become simultaneously available for left and right responses. The RI schedules were arranged for pecks on left and right white disks positioned on the screen as described for the initial links of the chains in Experiment 1.

RESULTS

The analysis was the same as the initial-link analysis in Experiment 1 (Equations 1 to 3). In both cases, we measured wait times from the end of reinforcer delivery. A plot of $N_L -$

N_R and $WT_R - WT_L$ computed session-by-session across the whole experiment, comparable to Figure 3, is shown in Figure 11. The squared correlations for all 3 pigeons were smaller than in Experiment 1, but the linear relation did not differ reliably in slope.

Figure 12 shows scatter plots of session-by-session response-rate ratios versus wait-time ratios, changeover-time ratios, and IRT ratios (comparable to Figure 4). There was a positive relation between response-ratio ratios and wait-time ratios, with squared correlations between .42 and .71. Correlations with IRT and changeover-time ratios were close to zero, and a log-survivor analysis of IRT proportions did not reveal a clear bout response pattern like that in Experiment 1.

We computed daily average left and right wait times and response rates following reinforcement for left and right responses. The results of Experiment 3 were similar to the results of Experiment 1: Both wait time and response rate on left and right schedules were similar following left and right reinforc-

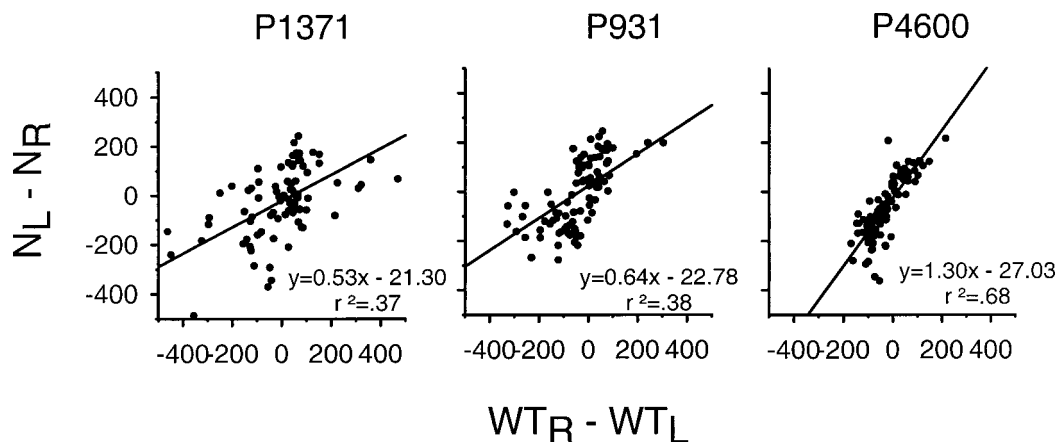


Fig. 11. Scatter plots of $N_L - N_R$ (session-average response-rate differences) versus $WT_R - WT_L$ (session-average wait-time differences) for subjects in Experiment 3 (see Figure 3 for further details). Best-fitting linear functions and r^2 values shown on plots were calculated using structural equations models and maximum-likelihood estimation methods.

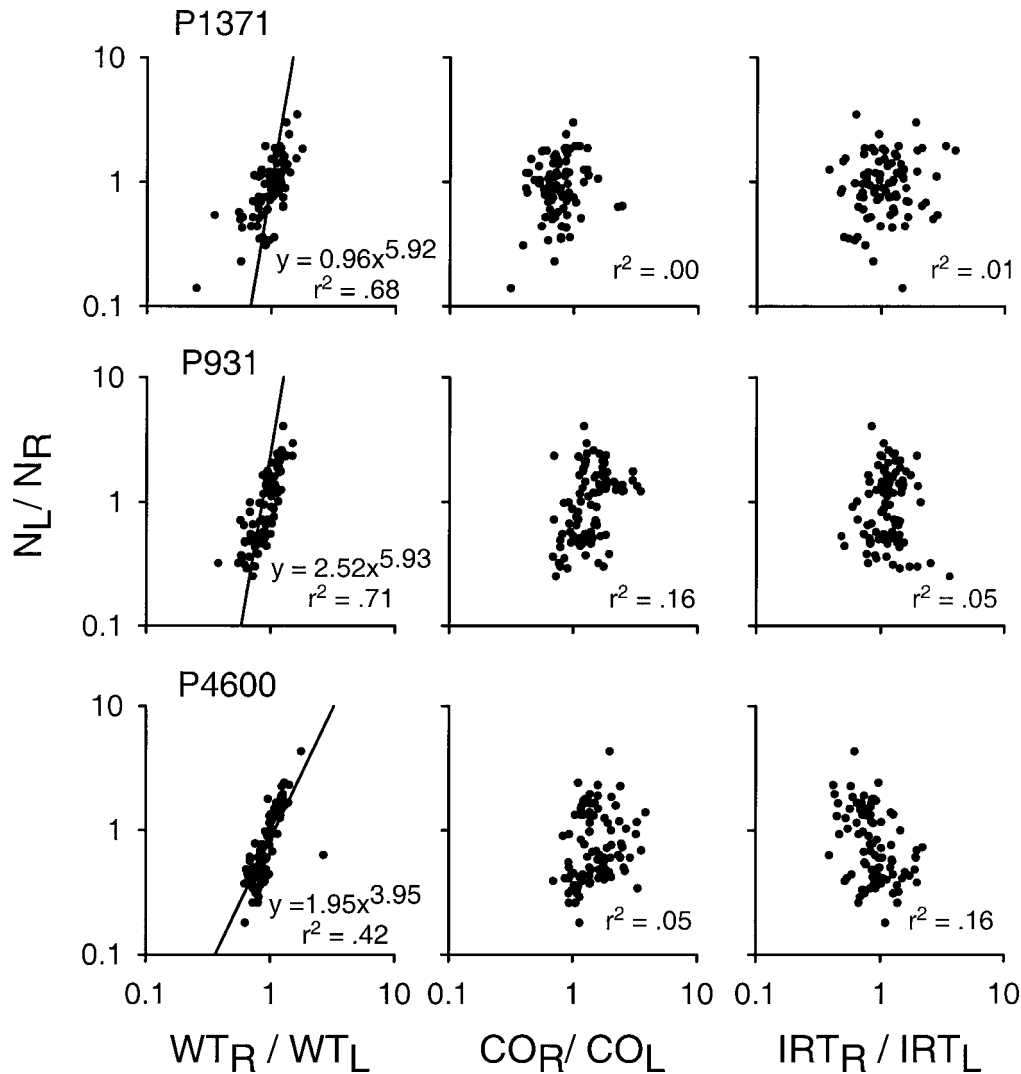


Fig. 12. Scatter plots of session-average relative response rates (N_L/N_R) versus relative wait times (W_T_R/W_T_L), changeover times (C_O_R/C_O_L), and IRTs ($I_R_T_R/I_R_T_L$) in Experiment 3 (see Figure 4 for further details). Fitted lines are not shown for the changeover and IRT data. Best-fitting linear functions and r^2 values shown on plots were calculated using structural equations models and maximum-likelihood estimation methods.

ers. As in Experiment 1, concurrent-schedule response rate varied across a wider range than wait time.

DISCUSSION

The results from the simple concurrent-schedule procedure were in most respects intermediate between those from the concurrent chain in Experiment 1 and the multiple concurrent chain in Experiment 2. The wait-time versus response-rate difference plots in Figure 11 showed similar linear relations as

in the concurrent-chain performance (Figure 3) and the multiple-chain performance (Figure 9), with squared correlations that were smaller than those in the concurrent chain but slightly larger than those in the multiple-chain performance. The wait-time ratio versus response-rate ratio plots in Figure 12 had a steeper slope and lower squared correlations than the comparable plots for concurrent-chain performance (Figure 4), but somewhat larger correlations than those from Experiment 2 (.42 to .71 vs. .11 to .70). The

range in wait times and response rates was less than in the concurrent-chain performance (Figure 3), mostly because of the larger pausing seen in concurrent chain schedules (Shull & Spear, 1987).

As in Experiments 1 and 2, response rates and wait times were similar irrespective of the immediately preceding source of reinforcement.

GENERAL DISCUSSION

On a concurrent chain RI FI schedule in which the short and long FI terminal links were switched every few days, we found that (a) initial-link wait-time differences and response-rate differences were linearly related (Equation 2 and Figure 3), and (b) session-average ratios of initial-link wait times and response rates, N_L/N_R and WT_R/WT_L , were related by a power function. The fit was closest in variance accounted for in the concurrent chain RI FI (Experiment 1) and weaker in the multiple chain RI FI and simple concurrent RI RI schedules. In all experiments, session-average initial-link response rates and wait times on the left and right did not depend on whether the previous reinforcer was for a left or a right response, and initial-link changes lagged behind terminal-link changes (Grace, 2002b). These results raise a number of general issues. We briefly describe two.

First, given the sensitivity of wait time to changes in time-to-reinforcement (Figure 7), it is of some interest to map out the steady-state relations between relative and absolute wait times and relative and absolute times to reinforcement on concurrent chain schedules. These data might provide an interesting parallel to the extensive concurrent-chain dataset already available relating relative and absolute terminal-link reinforcer rates and initial-link response rates. Because wait times can be meaningfully measured on FI as well as VI in initial- and terminal-link schedules, this research may facilitate the theoretical integration of choice data on all types of interval schedules.

Second, these data suggest a new way to look at free-operant choice theory. The traditional view is that preference (measured as relative response rate) is an indication of relative response strength. This view has yielded an impressive set of steady-state, molar, em-

pirical laws and accompanying theory, beginning with the matching law (Herrnstein, 1961) and continuing with a still-evolving set of theories of responding on concurrent chain schedules (e.g., Davison & Temple, 1973; Grace, 1994; Herrnstein, 1964; Killeen, 1982; Killeen & Fantino, 1990; Mazur, 1997, 2001; Squires & Fantino, 1971; Williams, 1988, 1994). But the approach has nevertheless encountered both theoretical and empirical difficulties (Staddon & Cerutti, 2003). Perhaps more attention to the temporal aspects of performance under these conditions can help us towards an integrated view of the enormous set of orderly data on reinforcement schedules.

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